

NEUTRINO EXPERIMENTS AND THEIR IMPLICATIONS

A. B. BALANTEKIN

*University of Wisconsin, Department of Physics
Madison, WI 53706, USA*

E-mail: baha@nucth.physics.wisc.edu

Recent developments in solar, reactor, and accelerator neutrino physics are reviewed. Implications for neutrino physics, solar physics, nuclear two-body physics, and r-process nucleosynthesis are briefly discussed.

1. Introduction

Solar neutrino experiments, especially with the announcement of recent results from the Sudbury Neutrino Observatory (SNO) ¹, have reached the precision stage. An analysis of the data from SNO as well as data from other solar neutrino experiments (Super-Kamiokande [SK] ³, Chlorine ⁴, and Gallium ^{5,6,7}), combined with the data from the reactor experiment KAMLAND ², place severe constraints on the neutrino parameters, especially mixing between first and second generations ^{8,9,10}. The neutrino parameter space obtained from such a global analysis, including the neutral-current results from the SNO salt phase, is shown in Fig. 1 ¹⁰.

The mixing angle between first and second generations of the neutrinos dominates the solar neutrino oscillations whereas the mixing angle between second and third generations dominates the oscillations of atmospheric neutrinos. There are several puzzles in the data. Both mixing angles seem to be close to maximum, very unlike the mixing between quarks. Also the third mixing angle, between first and third generations, seems to be very small, even possibly zero. It is especially important to find out if this mixing angle is indeed different from zero since in the mixing matrix it multiplies a CP-violating phase. Such a CP-violation may have far reaching consequences. To explain the baryon excess (over antibaryons) in the Universe, Sakharov pointed out that it may be sufficient to satisfy three conditions: i) Baryon number non-conservation (which is readily satisfied by the grand unified theories), ii) CP-violation, and iii) Non-equilibrium conditions. It

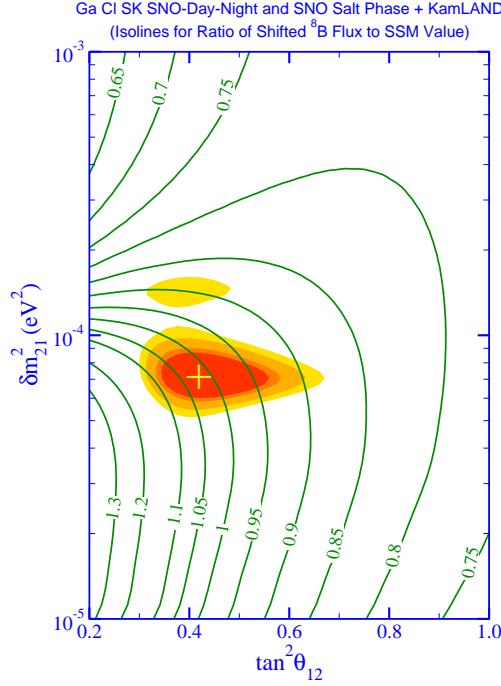


Figure 1. Allowed confidence levels from the joint analysis of all available solar neutrino data (chlorine, average gallium, SNO and SK spectra and SNO salt phase) and KamLAND reactor data. The isolines are the ratio of the shifted ^8B flux to the SSM value. At best fit (marked by a cross) the value of this ratio is determined to be 1.02 (from Reference 10).

is entirely possible that the CP-violation necessary for the baryogenesis is hidden in the neutrino sector.

It is worth pointing out that high-precision solar-neutrino data have potential beyond exploring neutrino parameter space. Here we discuss two such applications to solar physics and to nuclear physics.

2. Limits on Solar Density Fluctuations

It was suggested that solar neutrino data can be inverted to extract information about the density scale height ¹¹ in a similar way the helioseismological information is inverted to obtain the speed of the sound throughout the Sun. Even though the precision of the data has not yet reached a point where such an inversion is possible, one can obtain rather strong limits on *fluctuations* of the solar density using the current solar neutrino data.

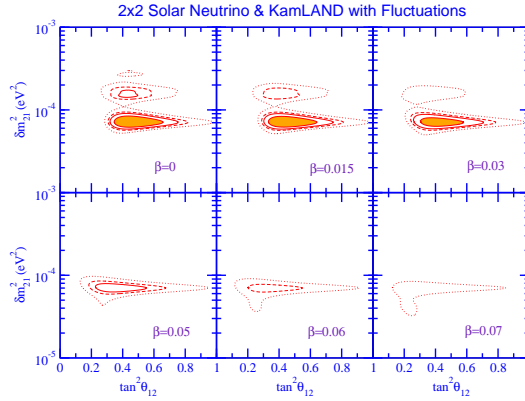


Figure 2. Allowed regions of the neutrino parameter space with solar-density fluctuations when the data from the solar neutrino and KamLAND experiments are used. The SSM density profile of Reference 14 and the correlation length of 10 km are used. The case with no fluctuations ($\beta = 0$) are compared with results obtained with the indicated fractional fluctuation. The shaded area is the 70 % confidence level region. 90 % (solid line), 95 % (dashed line), and 99 % (dotted line) confidence levels are also shown (From Reference 15).

To do so one assumes¹² that the electron density N_e fluctuates around the value, $\langle N_e \rangle$, predicted by the Standard Solar Model (SSM)¹⁴

$$N_e(r) = (1 + \beta F(r)) \langle N_e(r) \rangle, \quad (1)$$

and that the fluctuation $F(r)$ takes the form of white-noise. It turns out that the effect of the fluctuations is more dominant when the neutrino parameters and the average density are such that neutrino evolution in the absence of fluctuations is adiabatic. There are two constraints on the value of the correlation length. One is a restriction in the applicability of our analysis. In averaging over the fluctuations we assumed that the correlation function is a delta function. In the Sun it is more physical to imagine that the correlation function is like a step function of size τ . Assuming that the logarithmic derivative is small, which is accurate for the Sun, delta-correlations are approximately the same as step-function correlations if the condition

$$\tau \ll \left(\sin 2\theta \frac{\delta m^2}{2E} \right)^{-1} \quad (2)$$

is satisfied¹³. A second constraint on the correlation length is provided by the helioseismology. Density fluctuations over scales of ~ 1000 km seem

to be ruled out. On the other hand current helioseismic observations are rather insensitive to density variations on scales close to ~ 100 km¹⁶.

The neutrino parameter space for various values of the parameter β was calculated in Reference 15 and is shown in Figure 2. These results, in agreement with the calculations of other authors^{17,18}, show that the neutrino data constrains solar density fluctuations to be less than $\beta = 0.05$ at the 70 % confidence level when τ is about 10 km. It is important to emphasize that the best fit to the combined solar neutrino and KamLAND data is given by $\beta = 0$ (exact SSM). Neutrinos interact with dense matter not only in the Sun (and other stars) but also in several other sites such as the early universe, supernovae, and newly-born neutron stars and neutrino interactions with a stochastic background may play an even more interesting role in those sites.

3. Two-Body Axial Current

In the effective field theory approach to nuclear interactions, nonlocal interactions at short distances are represented by effective local interactions in a derivative expansion. Since the effect of a given operator on low-energy physics is inversely proportional to its dimension, an effective theory valid at low energies can be written down by retaining operators up to a given dimension. It turns out that the deuteron break-up reactions

$$\nu_e + d \rightarrow e^- + p + p \quad (3)$$

and

$$\nu_x + d \rightarrow \nu_x + p + n, \quad (4)$$

observed at SNO, are dominated by a ${}^3S_1 \rightarrow {}^3S_0$ transition, hence one only needs the coefficient of the two-body counter term, commonly called L_{1A} , to parameterize the unknown isovector axial two-body current¹⁹. Chen, Heeger, and Robertson, using the SNO and SK charged-current, neutral current, and elastic scattering rate data, found²⁰ $L_{1A} = 4.0 \pm 6.3$ fm³. In order to obtain this result they wrote the observed rate in terms of an averaged effective cross section and a suitably defined response function. One can explore the phenomenology associated with the variation of L_{1A} . For example the variation of the neutrino parameter space, which fits the SNO data, as L_{1A} changes was calculated in²¹ and is shown in Figure 3. In Reference 21 the most conservative fit value with fewest assumptions is found to be $L_{1A} = 4.5^{+18}_{-12}$ fm³. (One should point out that if the neutrino parameters were better known one can get a much tighter limit). It was also

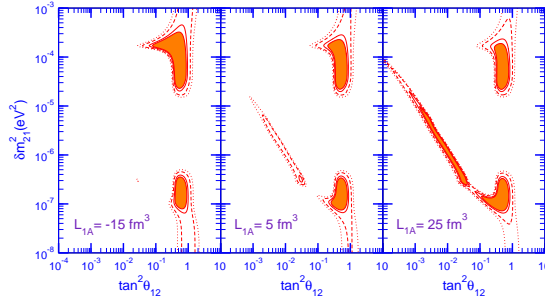


Figure 3. The change in the allowed region of the neutrino parameter space using solar neutrino data measured at SNO as the value of L_{1A} changes. The shaded areas are the 90 % confidence level region. 95 % (solid line), 99 % (log-dashed line), and 99.73 % (dotted-line) confidence levels are also shown (From Reference 21).

shown that the contribution of the uncertainty of L_{1A} to the analysis and interpretation of the solar neutrino data measured at the Sudbury Neutrino Observatory is significantly less than the uncertainty coming from the lack of having a better knowledge of θ_{13} , the mixing angle between first and third generations.

4. Implications for r-process Nucleosynthesis

There is another puzzling experimental result. The Los Alamos Liquid Scintillator Neutrino Detection (LSND) experiment has reported an excess of $\bar{\nu}_e$ -induced events above known backgrounds in a $\bar{\nu}_\mu$ beam with a statistical significance of 3 to 4 σ ^{22,23}. The mass scale indicated by the LSND experiment is drastically different than the mass scales implied by the solar and atmospheric neutrino experiments. Since to get three different differences one needs four numbers, a confirmation of the LSND result by the mini-BooNE experiment represents evidence for vacuum neutrino oscillation at a new δm^2 scale. Discovery of such a mixing would imply either CPT-violation in the neutrino sector, or the existence of a light singlet sterile neutrino which mixes with active species. The latter explanation may signal the presence of a large and unexpected net lepton number in the universe. The existence of a light singlet complicates the extraction of a neutrino mass limit from Large Scale Structure data. It may also have implications for core-collapse supernovae, which is one of the leading candidates for the site of r-process nucleosynthesis ²⁴. A sterile neutrino scale implied by the LSND experiment may resolve some outstanding problems preventing a successful nucleosynthesis. Formation of too many alpha par-

titles in the presence of a strong electron neutrino flux coming from the cooling of the proto-neutron star, known as the alpha effect^{25,26}, may be prevented by transforming active electron neutrinos into sterile neutrinos^{27,28,29,30}. One can find the appropriate mass scale to achieve this goal^{27,30} which seems to overlap with the LSND mass scale.

R-process nucleosynthesis requires a neutron-rich environment, i.e., the ratio of electrons to baryons, Y_e , should be less than one half. Time-scale arguments based on meteoritic data suggests that one possible site for r-process nucleosynthesis is the neutron-rich material associated with core-collapse supernovae^{31,32}. In one model for neutron-rich material ejection following the core-collapse, the material is heated with neutrinos to form a “neutrino-driven wind”^{33,34}. In outflow models freeze-out from nuclear statistical equilibrium leads to the r-process nucleosynthesis. The outcome of the freeze-out process in turn is determined by the neutron-to-seed ratio. The neutron to seed ratio is controlled by the expansion rate, the neutron-to-proton ratio, and the entropy per baryon. Of these the neutron-to-proton ratio is controlled by the flavor composition of the neutrino flux coming from the cooling of the proto-neutron star. Hence understanding neutrino properties (including the impact of neutrino-neutrino scattering in neutrino propagation³⁵) could significantly effect our understanding of the r-process nucleosynthesis.

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